

**Economic Assessment of Advanced Biomass
Gasification Systems**

**in
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ECONOMIC ASSESSMENT OF ADVANCED BIOMASS GASIFICATION SYSTEMS

INTRODUCTION

Science Applications International Corporation (SAIC), under the sponsorship of the U.S. Department of Energy (DOE), is conducting engineering and economic studies to assess advanced biomass conversion technologies. The objective of this paper is to summarize an economic evaluation of three advanced biomass gasification technologies being developed with U.S. Government funding. These advanced systems are designed to produce low-pressure medium-Btu fuel gas (300-500 Btu/SCF) from wood feedstocks. These systems are:

1. An atmospheric-pressure multi-solid entrained-flow gasifier being developed by Battelle Columbus Laboratory (BCL).
2. An atmospheric-pressure oxygen-blown downdraft fixed-bed gasifier being developed by Syngas, Inc., based upon technology originally developed at Solar Energy Research Institute (SERI).
3. An indirectly-heated fluidized-bed gasifier being developed at the University of Missouri-Rolla (UM-R).

Pressurized gasification systems, such as the fluidized-bed gasifier being developed by the Institute of Gas Technology, for applications requiring high-pressure synthesis gas are not included in this assessment.

This evaluation of these advanced biomass gasification processes consisted of the following elements, which are presented in this paper:

- Description of gasifier design features and operating characteristics based on recent reports and data packages prepared by the system developers (1,2,3). (More complete final reports which became available recently for these systems (4,5,6) were also reviewed for this paper.) The experimental data were reviewed, and where appropriate, additional correlations were developed and conclusions noted.
- Analysis of integrated conceptual gasification system designs. For these system designs a test case or cases were selected for each system based upon the experimental data for the gasifier. Material and energy balances were then calculated for each system design to develop an estimate for system efficiency based upon a complete gasification plant.
- Economic analysis of complete 200-TPD and 1000-TPD gasification plants. These sizes were chosen to illustrate the scale-up potential for the different gasification systems.

DESCRIPTION OF BIOMASS GASIFICATION TECHNOLOGIES

Battelle Columbus Laboratory Gasification System

The Battelle biomass gasification process (1,4) is designed to produce a medium-Btu product gas without using oxygen. The process uses two physically separate zones: (1) a gasification zone in which the biomass is converted into residual char and a medium-Btu gas, and (2) a separate combustion zone in which the char and the tar are burned to provide the heat required for gasification. Heat transfer between zones is accomplished by circulating sand between the gasification zone and the combustion zone. The schematic process flowsheet in Figure 1 illustrates the basic concept. This basic concept has also been applied to coal gasification and gasification of municipal solid wastes.

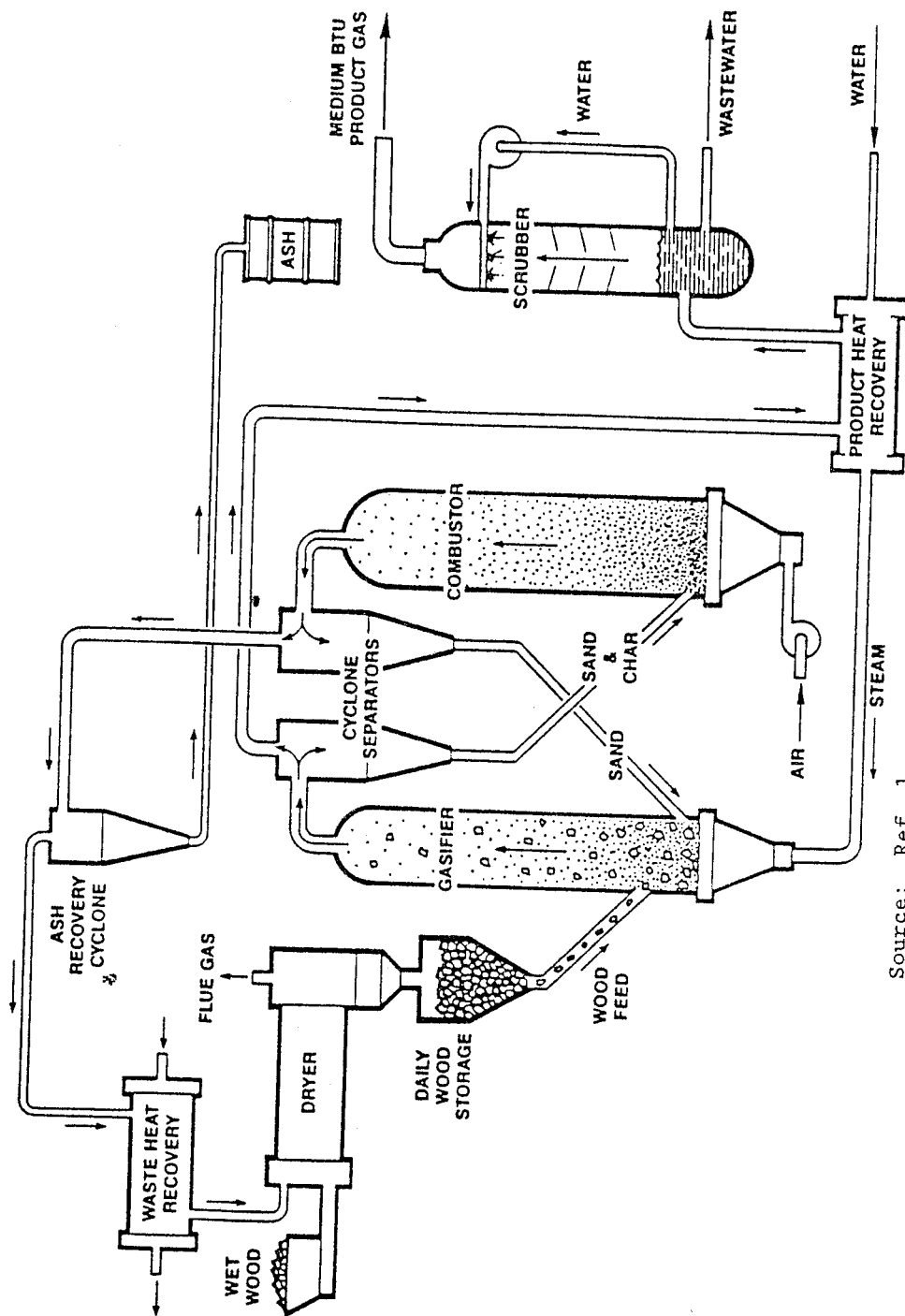
The Battelle process is designed to exploit the high reactivity of biomass with the development of a reactor system capable of high processing throughputs. The Battelle process will ordinarily be used to provide a cooled, clean 450-500 Btu/SCF* product gas. Waste heat in the flue gas from the combustor can be used to preheat incoming air and then to dry incoming wood. The condensed organic phase scrubbed from the product gas is separated from the scrubber water, in which the condensed organics are insoluble, and injected into the combustor. As Figure 1 indicates, the net products from the process are the cooled cleaned product gas, wood ash, and treated wastewater.

The Process Research Unit (PRU) that Battelle is using to develop the process was designed as a flexible system capable of simulating integrated operation of the gasification/char combustion system. The system currently consists of a 10-in. I.D. gasifier coupled to a 40-in. I.D. combustor. The system has been operated at wood feed rates of from 50 to 1900 lb/hr. The BCL PRU has been in operation since 1980. A total of 142 test runs have been completed to study the most important gasification process parameters.

The primary reaction products generated in the gasifier are, in order of yield: product gas, char, and a very low yield of organic condensate. The product gas composition remains very constant regardless of the values selected for the operating parameters or feed gas. The relative yields of char and product gas were found to depend almost entirely on temperature with other parameters having, at most, a second-order effect on the distribution between char and product gas. Therefore, gasifier temperature appears to be the only parameter of significance in determining the conversion of biomass into a medium-Btu gas.

The carbon conversion level is critical in determining the commercial feasibility of the process because the system heat balance requires that the heat for gasification be provided by burning the residual char, or some other fuel, in the combustor. The system is said to operate in thermal balance when the carbon conversion is

*In this paper, except where noted otherwise, the conditions for an SCF of gas are 1 atm, 60°F.



Source: Ref. 1.

FIGURE 1. Battelle's Biomass Gasification System.

sufficiently high to allow the combustor to operate at a reasonable temperature ($<2000^{\circ}\text{F}$) with reasonable air preheat (750°F) with the only means of heat removal from the combustor being the circulation of sand between gasifier and combustor. Because the PRU is small with significant heat losses, the PRU can not be operated in thermal balance with only char being burned in the combustor; natural gas is used as an auxiliary fuel in PRU tests to compensate for heat losses. Assuming heat losses typical of commercial-sized plants, the system will be in thermal balance at a carbon conversion to product gas of about 68 to 75 percent depending on the moisture level. All of the carbon conversion-to-gas data points generated in both 6- and 10-in. I.D. gasifiers are shown in Figure 2, with the correlating line showing the least-squares fit of the data. These results indicate that the carbon conversions required for balanced operation in commercial-sized plants can be achieved by operating at gasifier temperatures in the 1500°F to 1600°F range.

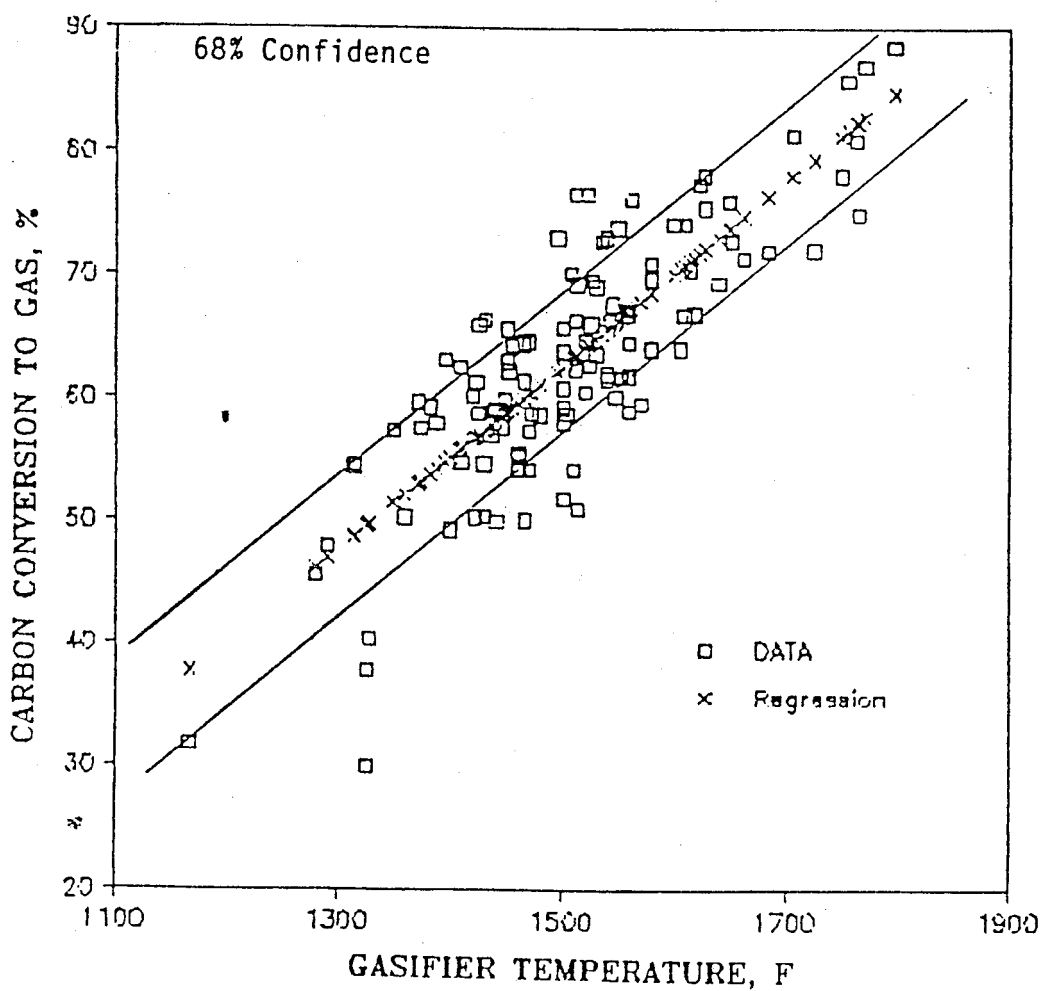
Based on the highest reported data, the economically important performance parameter of throughput is higher in the Battelle process than has been reported for any other biomass gasification process. A number of test runs have demonstrated the ability of the Battelle process to achieve gasifier throughputs of up to approximately $3000\text{ lb/ft}^2\text{-hr}$.

An examination of the detailed data indicates that the gas heating value is essentially constant regardless of the particular operating conditions or wood type. One of the most significant results is that the dry gas heating value of the product gas is independent of the moisture content of the wood. This result is in sharp contrast to the behavior of single-zone gasifiers such as air- or oxygen-blown fluid-beds where the dry gas heating value is greatly dependent on the wood moisture.

In either the two-zone Battelle process or single-zone gasification systems, more char must be burned to generate the heat required to evaporate the additional moisture. However, in the Battelle process the combustion of char is physically separate from the gasification zone, which means that the additional nitrogen and carbon dioxide from the combustion of the additional char is not mixed with the product gas as in a single-zone process.

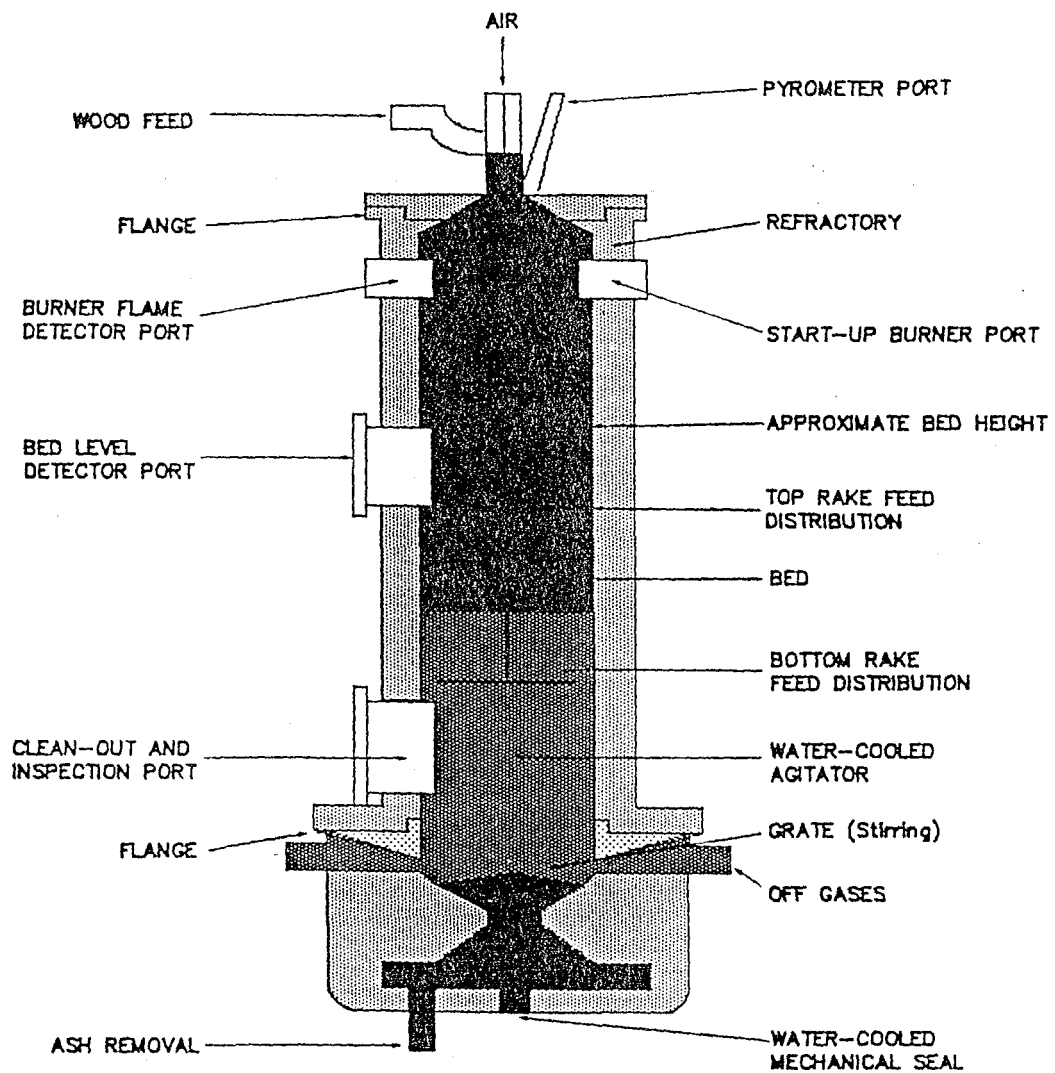
Syngas Downdraft Gasifier

The Syngas gasification system (2,5) is sized to produce 10 MMBtu/hour (hot Lower Heating Value [LHV] basis) of product fuel gas from approximately 1650 lb/hour (15 percent moisture content, wet basis) of wood fuel to the downdraft gasifier. The gasifier is a prototype downdraft gasifier based on the SERI technology. Figure 3 is a schematic of the gasifier. The reactor is constructed of carbon steel and is refractory lined. The solid wood feed is fed at a rate in excess of $2\text{ MMBtu/ft}^2\text{-hr}$ (Lower Heating Value basis) concurrently with air or oxygen, which is fed through the central air pipe. Wood falls into the 30-in. I.D. top zone of the gasifier, where flaming pyrolysis is allowed to occur on the surface of the bed. Partially combusted pyrolysis gas flows through the resulting char bed where it reacts further with char and is disengaged in the plenum section of the



Source: Ref. 1.

FIGURE 2. Carbon Conversion to Gas for Battelle's System.



Source: Ref. 2.

FIGURE 3. Preliminary Syngas Gasifier Design.

reactor. Ash material is extracted using a hydraulic ratcheting rotating grate. The internal dimensions and nature of the internals are proprietary to Syngas, Inc.

The Syngas demonstration facility has been operated on woodchip feedstock with pure oxygen as the gasification medium. Data are reported on a total of ten runs with oxygen with different types of feed, feed rates, and temperatures. The overall conclusion from the testing to date is that medium-Btu gas can be successfully produced by oxygen-blowing in a large-size downdraft gasifier. The gas produced had a wet, lower heating value in excess of 250 Btu/SCF and a dry, tar-free higher heating value in excess of 300 Btu/SCF. Downdraft wood gasification requires no steam input to the reactor whether air or oxygen is employed.

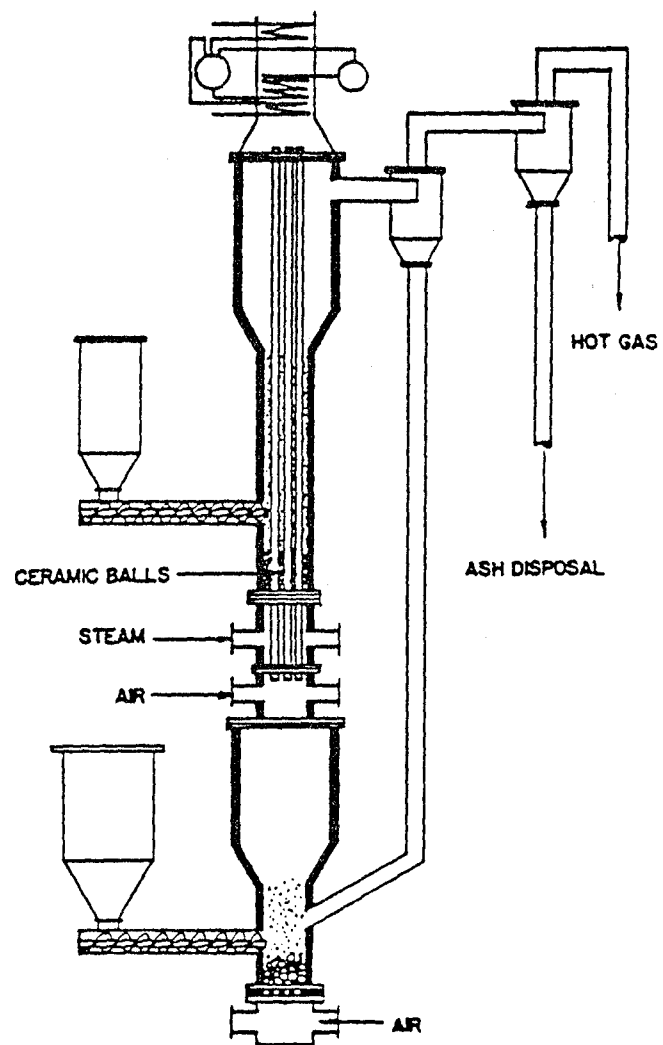
University of Missouri-Rolla Indirect-Fired Fluidized-Bed Gasifier

The gasifier in the University of Missouri-Rolla biomass gasification system (3,6) is an indirect-fired fluidized-bed reactor. The reactor consists of three major components: a fluidized-bed reactor, a fire-tube bundle of 30 U-tubes, and two propane burners mounted in the combustion chamber. The reactor is a stainless steel cylinder with a 20-in. I.D., and 17 feet high with the tube bundle inserted and several access ports. This pilot gasifier is fired by the propane burners in the lower combustion chamber. The hot combustion gases are used to transfer heat to the fluidized bed of biomass via the heat-transfer tubes extending into the fluidized bed.

For commercial adaptation of the indirect-heated gasifier technology, the propane burners and the combustion chamber would be replaced by a low-Btu biomass gasifier. This reactor design is shown in Figure 4. The unit is constructed by placing the medium-Btu gasifier on top of a two-stage low-Btu gasifier. The low-Btu gasifier is the same technology developed in the original gasification work at the University of Missouri-Rolla facility. Combustion air is added to a combustor at the bottom of the medium-Btu gasifier for the controlled combustion of the low-Btu gas to develop the flue gas temperature necessary for the heat transfer through the tubes in the medium-Btu system. At the same time the air addition will be sufficient to burn the tar and char in the gas stream, providing a clean gas for the heat-transfer process.

Data have been obtained from 118 runs conducted to provide insight into the important gasification parameters. The parameters that were varied included: gasifier temperature (from 1051°F to a maximum of 1466°F), wood feed rate, and steam rate. From the data it is possible to determine gasifier performance and to estimate the quantity of gas produced, the heating value of the gas on a dry basis, and the resulting amounts of tar and char. These quantities are estimated from the independent design variables, namely, the reactor bed temperature and the steam-to-wood ratio.

The reactor bed temperature has primary influence on the gasification process in this system and was chosen as the main correlation variable. The steam-to-wood (s/w) ratio has secondary impact and is used as a parameter. Three levels of the steam-to-wood



Source: Ref. 3.

FIGURE 4. Commercial UM-R System Design.

ratio were used and designated as low, medium, and high corresponding to $s/w < 1.2$, $1.2 < s/w < 2.0$, and $s/w > 2.0$, respectively. The heating value of the product gas decreases with increasing bed temperature at any steam-to-wood ratio. Operation at the medium steam-to-wood ratio produced the highest heating values. Low ratios resulted in minimal fluidization; high ratios produced a lean fluidized bed.

Char production is the same at all temperatures. The amounts of char and tar produced affect the total energy content of the product gas. The decrease in tar production at essentially constant char production leads to an increase in product gas energy. The total energy of the product gas increases with increased bed temperature. Because the heating value of the gas decreases with temperature, the amount of gas produced increases.

Steam consumption is a parameter of economic and operational significance. The minimum steam rate was fixed by the need to maintain fluidization of the bed. The steam-to-wood ratio was varied from 0.7 to 3.3. Best operation for a high heating value appears to be at a medium steam-to-wood ratio of 1.5. This condition is sufficient to keep the bed well fluidized. Lower steam rates severely limited fluidization. Higher rates favored slightly higher H_2/CO ratios, thereby lowering the heating value of the product gas.

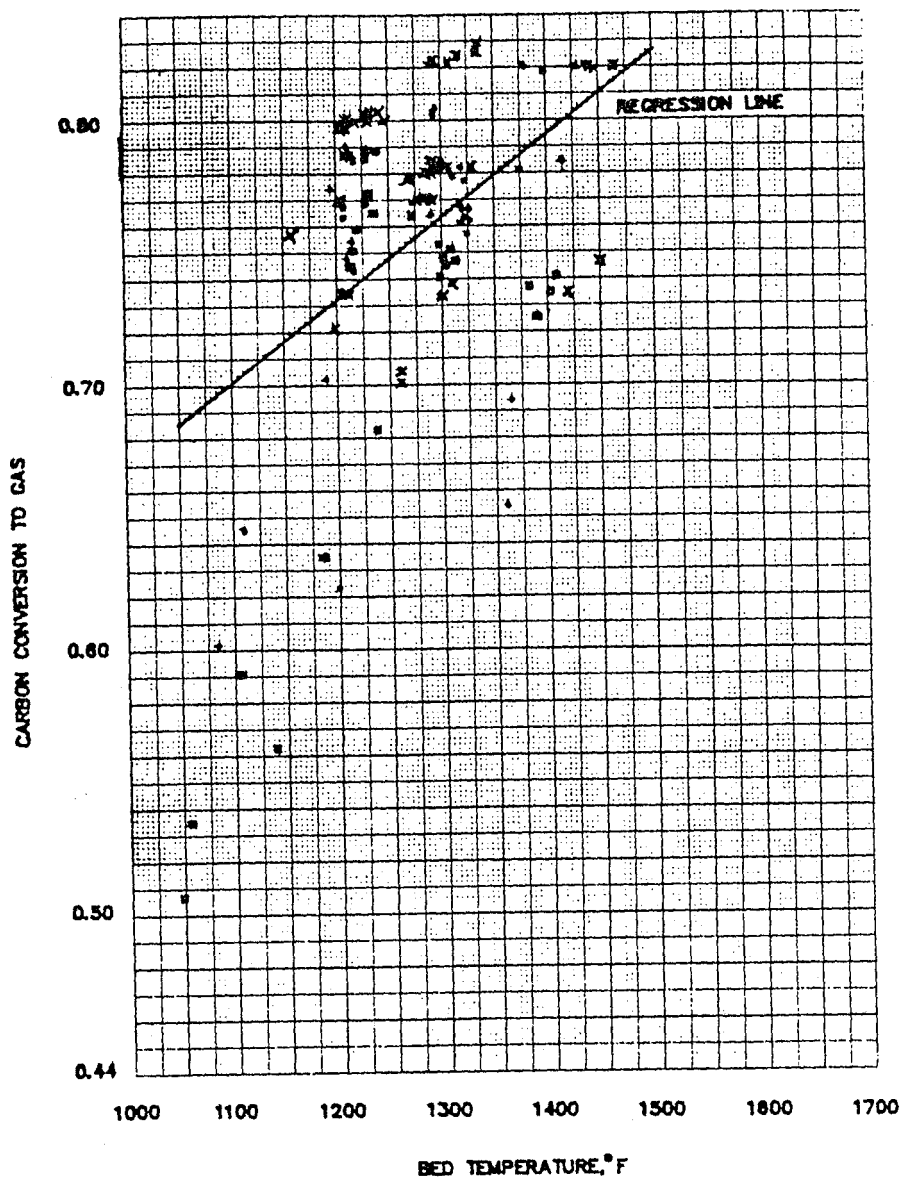
In the selection and analysis of test cases used as the bases for conceptualized integrated plants, it was necessary to develop additional correlations of the data. One such correlation was of the carbon conversion to gas with bed temperature. To correct for discrepancies in the carbon balance (which generally was closed to within $\pm 10\%$), the original data on carbon in the output products--gas, char, and tar--were normalized to the total carbon input, in effect making the assumption that the product split was correct. This procedure then assured that the carbon balance for the test cases would be closed.

These corrected data on carbon conversion to gas were plotted against bed temperature with steam-to-wood ratio as a parameter. This plot is shown in Figure 5. The three groups of data for the three regions of steam-to-wood ratio do not appear to form separate correlations, but are completely intermingled. Hence, all of the data were used to calculate a least-squares regression line, which is shown in the figure. The data do not appear to be a function of steam-to-wood ratio, in contrast to the assertion of the system developers.

Although all of the data were used in the regression, the regression line is influenced significantly by the large amount of data at temperatures greater than $1200^\circ F$. The data below $1200^\circ F$ are very sparse; to define the correlation below this temperature would require taking more data in this temperature regime.

Summary of Biomass Gasification System Characteristics

A summary of the design and operating characteristics for the three advanced biomass gasification systems evaluated in this study is found in Table 1. The data given in this table for gasifier operating



STEAM-TO-WOOD RATIO:

| | |
|--------------|---|
| < 1.2 | x |
| ≥ 1.2, < 2.0 | o |
| ≥ 2.0 | □ |

FIGURE 5. Carbon Conversion to Gas (corrected data) vs. Bed Temperature -- UM-R System.

TABLE 1. Summary of Design and Operating Characteristics
of Three Advanced Biomass Gasification Systems.

| | System | | |
|--|--|---|---|
| | Battelle Columbus | Syngas, Inc. | University of Missouri-Rolla |
| Design Characteristics: | | | |
| Reactor type | entrained-flow gasifier | fixed-bed vertical vessel (downdraft gasification) oxygen | indirect-fired fluid-bed system |
| Gasification medium | steam or recycled product gas (not demonstrated) | | steam |
| Gasifier heating mechanism | recirculating sand heated in separate combustor | flaming pyrolysis on top of bed (startup proprietary) | indirect heat |
| Steam generation for gasifier and heat to dryer | combustion of char plus waste heat recovery | no steam used | waste heat recovery from flue gas from combustion zone |
| Prototype unit size | 25 TPD 10 in. I.D. x 22 ft height | feed rates up to 2000 lb/hr (15 MMBtu/hr [LHV] input) 30 in. I.D. x 13 ft height | 400 lb/hr feed rate 20 in. I.D. x 17 ft height |
| Feedstock characteristics | wide variety tested, from sawdust to chips to coarsely shredded material. | cedar and pine woodchips 5-25% moisture contents (coarse fuels more suitable than fine) | no information |
| Feedstock preparation | none required, predrying accomplished with waste heat. Screening to remove tramp material. | dried fuels required (<25%). prototype has no fuel drying capability. Fuels used are -6 inch with varying fines. Some screening done to remove fines. | no special preparation indicated |
| Product gas cleanup | gas cleaned of particulates and sand with a hot cyclone. Gas then goes to waste heat recovery to generate steam and a scrubber to collect condensed organics, which are injected into combustor. heating value of product gas independent of feed moisture level. Gasifier temperature only significant parameter determining conversion. Sep- arate gasification/combustion zones. | gas cleaned of particulates with a hot cyclone. Gas can then be cooled and cleaned further in a baghouse. No provision for tar removal. | gas is cleaned of char with a hot cyclone and is then scrubbed in a venturi scrubber. Cleaned gas then goes through tar drop-out drums and demister. Tar is allowed to settle out of water. |
| Remarks | | gasifier designed for air blowing; its use with O ₂ necessitates some modifi- cations. Closure of heat and material balances is attempted using the direct data and is not forced. Not much data available. | indirect heat is provided by gasi- fying, with subsequent combustion of the gas, additional biomass feed. Additional feed required for commercial design is about 0.99 lb dry biomass to provide heat per lb dry wood to produce medium-Btu gas, but excess heat would be available. |

TABLE 1. Summary of Design and Operating Characteristics
of Three Advanced Biomass Gasification Systems. (Continued)

| | System | | |
|--|---|--|---|
| | Battelle Columbus | Syngas, Inc. | University of Missouri-Rolla |
| Gasifier Operating Conditions—Range (Baseline Case ¹): | | | |
| Temperature, °F | 1300-1800 (1525) | 1600-1700 (1600) | 1050-1450 (1300) |
| Pressure, psig | < 15 | < 15 | < 15 |
| Feed throughput in gasifier, lb/ft ² -hr | 3000 (gasifier) | < 395 (not necessarily the maximum) | 140 |
| Moisture content of gasifier feed, % | up to 48 (11.3) | 5-25 (10) | 10 (10) |
| Steam rate, lb/lb dry wood | minimum 0.3 (0.311) | none | 0.7-3.3 (0.733) |
| Oxygen, lb/lb dry wood | none | (0.18) ³ | none |
| HHV of product gas (dry), Btu/SCF | 450-500 (454) | (319.0) | 350-550 (450) |
| Product gas (dry) composition, % vol | | | |
| C ₁ + | 1.7-9.4 (5.3) | 2.2-2.4 (2.2) | 3.2-8.4 (5.5) |
| CH ₄ | 12.3-18.6 (16.0) | 5.2-6.2 (5.2) | 6.4-20.2 (12.0) |
| CO | 35.9-54.8 (43.3) | 39.2-45.2 (44.4) | 19.5-53.4 (40.0) |
| CO ₂ | 7.0-21.6 (14.2) | 24.6-30.2 (26.7) | 12.6-27.1 (20.0) |
| H ₂ | 8.6-35.6 (20.4) | 21.2-22.1 (21.5) | 12.9-41.6 (20.0) |
| N ₂ | (0.7) | — | 0.2-3.5 (1.5) |
| Char production, lb/lb dry wood | (0.169) ² | (0.069) | 0.04-0.08 (0.06) ⁴ |
| Tar production, lb/lb dry wood | 0.005-0.01 (0.005) ² | (0.034) | 0.07-0.10 (0.08) ⁴ |
| Tar/Oil characteristics | highly condensed aromatic compounds, few oxygenated compounds | 77.2% C | 69.2% C, little O |
| Carbon conversion to product gas, % | gasifier only 50-85 integrated system for thermal balance 68-75 (68.3) | (90) | gasifier only 60-81 (67) ⁵ |
| Cold gas thermal efficiency, (HHV product gas/HHV wood feed), % | integrated system 68-75 (68.0) | (64.3) | gasifier only 60-81 (60) ⁵ |
| Product gas (dry) yield, SCF/lb dry wood | integrated system 11.5-14.5 (12.7) | (18.7) | gasifier only 10.8-16.5 (11.8) ⁵ |

¹An example system from developer's report. For high-efficiency test cases, see section 3.

²Produced in gasifier, combusted in combustor in integrated system—no net output from system.

³Data appears low. Value calculated from material balance is 0.48.

⁴Produced in gasifier, combusted in low-Btu gasifier to provide heat—no net output.

⁵These figures are not for an integrated plant and do not include the biomass combusted in the low-Btu gasifier to provide heat for the gasification in the medium-Btu gasifier.

conditions illustrate the range of conditions used in experimental tests and the range of results obtained. Specific cases are also given.

Some care must be used to compare the data shown in the table for the different systems because in two cases (Battelle Columbus and University of Missouri-Rolla) the complete system includes a separate combustor to provide heat, in addition to the gasifier, and the figures shown are for the gasifier only. In addition, the specific cases do not necessarily illustrate the conditions for high system efficiency. In the next section of this paper, test cases are developed on the basis of analyzing all of the data for each system to describe a high-efficiency operation for each complete gasification system.

CONCEPTUAL DESIGNS OF INTEGRATED BIOMASS GASIFICATION PLANTS

Introduction

In this section conceptual designs of integrated biomass gasification plants are presented and discussed. These integrated plants were designed around test cases for the three biomass gasifiers evaluated in this report. For each gasifier design one or two test cases were prepared based upon the gasifier performance data. The test cases were selected and prepared to represent each gasifier's best demonstrated performance and to be representative of the experimental data.

As the result of analyzing the experimental data, gasifier test cases were calculated for a 200-TPD (dry) plant and were used as the basis for integrated gasification plants. The input to the integrated plant would be woodchip feedstock and its output medium-Btu fuel gas. The purpose of developing designs for integrated plants was to compare gasifier designs on the basis of overall system efficiencies which would consider the possible need for auxiliary fuel, either to dry the incoming green woodchips or to raise the steam that may be needed for the gasification process.

Overall plant energy efficiencies were also calculated which considered the amount of electricity required, either for electrical power or for oxygen production. The electricity required was evaluated in terms of the primary energy consumed to produce it. The next part contains further analysis of gasifier test data and the selection of the gasifier test cases for the integrated plants. Block flow diagrams of the conceptual designs of integrated plants are then presented, and the process flows and process design of each plant are discussed.

Selection of Test Cases for Gasifier Systems

For each gasifier design one or two test cases were prepared based upon the gasifier performance data. The test cases were selected and prepared to represent each gasifier's best demonstrated performance and to be representative of the experimental data. Thus, test cases were selected on the basis of best efficiency, particularly cold gas thermal efficiency, which is the ratio of the heat of combustion of the product

gas on a cold dry basis to the high heating value of the wood feedstock. Experimental data were also correlated and averaged before being used as the basis for a test case. The purpose of this procedure was to avoid basing a test case upon a single experimental test run which could be unrepresentative, biased, and significantly different from the mass of the data. The test cases were also to be based solely upon the available data and not to be the result of extrapolating the data to untested conditions with unverified results. Because different feedstocks were used for the tests with the different gasifiers, the test cases were based upon these different feedstocks.

Battelle Columbus Laboratory Gasification System. According to the BCL data, the most significant operating parameter is the gasification temperature, which determines the carbon conversion to gas. As the carbon conversion to gas increases, the cold gas thermal efficiency also increases, up to a point. For a feedstock with a given moisture content, there is a maximum carbon conversion to gas, at a maximum gasification temperature, which can be obtained in a balanced operation between gasifier and combustor without using auxiliary fuel in the combustor.

According to BCL, the range of maximum carbon conversions to gas which would result in balanced operation of a commercial-sized plant is 68-75 percent. The corresponding range of gasification temperatures is 1500-1600°F. One question that needs to be addressed is whether or not it is worthwhile, in terms of efficiency, to use auxiliary fuel in the combustor to increase the carbon conversion to gas in the gasifier above this range for balanced operation.

Two test cases were therefore examined. In one case a gasification temperature of 1600°F was selected as the maximum temperature which could be obtained for balanced operation with a feedstock containing 10 percent moisture. The carbon conversion to gas was 70 percent (Figure 2). In another case a gasification temperature of 1857°F was chosen as the maximum practical temperature which has been demonstrated in the system. For this latter case the objective was to see what effect using auxiliary fuel would have on the cold gas thermal efficiency.

Because the steam-to-wood ratio has been shown to have small influence on the process performance--gas composition, thermal efficiency, etc.--the minimum ratio of 0.3 lb steam/lb wood was selected for the test cases. Indeed, because the only use for the steam in the process is for fluidizing the feedstock in entrained flow, Battelle has suggested that recycled product gas be used for this purpose. With the selection of the operating conditions of gasification temperature and steam-to-wood ratio, the test cases could be calculated. For a balanced operation of the BCL system, the overall energy balance around both gasifier and combustor has to be satisfied. If necessary, the outlet temperature of the flue gas from the combustor may have to be adjusted to balance the system. The final solution would be a satisfactory one if all operating parameters were determined to be in the practical operating range as defined by Battelle.

The results of the calculations for the test case at a gasification temperature of 1600°F are shown in Figure 6 and summarized in Table 2. The cold gas thermal efficiency was found to be 72.6 percent. The results of the calculations for the test case at 1857°F showed that the use of auxiliary fuel in the combustor lowers the cold gas efficiency, in this case to 69-70 percent, depending on the outlet temperature of the combustor flue gas.

Syngas Downdraft Gasifier. The developer's data on the Syngas downdraft gasifier presented some additional problems in analyzing and using the data to calculate a test case for an integrated gasification plant. First, not very much data were available. Data were reported for only seven runs (2) with oxygen with different types of feedstock, feed rates, and temperatures. Material balances were presented for only two runs and were closed only to within +15 percent. There was no attempt to close the balances; nor was there any explanation or analysis to indicate the sources of error.

The two runs with material balances were both conducted at a bed temperature of 1600°F with the same feedstock at similar feed rates. It was therefore decided to average the results of these two runs (average carbon conversion and average gas composition) to obtain a test case for an integrated plant. The gas composition data for these two runs first had to be corrected for the effects of an estimated CO₂ purge and, in the case of one run, a sample system air leak. The corrected gas compositions were very consistent and were also comparable with the gas compositions reported for other runs at 1600°F.

The carbon balance for each of the two runs analyzed showed 4 to 7 percent more carbon output than was input. The figures could be corrected by assuming either that the amount of carbon in the gas was correct (indeed, it was stated that the amount of tar reported was an estimate) or that the split of the carbon among the three output products--gas, char, and tar--was correct. Actually, the calculations were done both ways; the results are discussed below.

The hydrogen and the oxygen material balances were of no help in understanding the carbon material balance. The hydrogen output was consistently lower than the input, and the oxygen output was consistently and substantially higher than the reported input.

In Figure 7 and Table 2 the results are presented for the calculations for the test case for the Syngas gasifier based on the assumption that the figures for the amount of carbon in the gas were correct. The material balance for this case showed that much more water vapor, which was calculated from a hydrogen balance, was produced than was indicated by the data. The oxygen balance then indicated that much more oxygen was required to be added to the system than was reported [0.48 lb O₂ consumed/lb wood (dry) versus 0.18-0.26 lb O₂ added/lb wood (dry)]. The calculated figure is actually more consistent with the oxygen consumption reported (0.42-0.44 lb O₂/lb wood) for the SERI downdraft gasifier (2), on which the Syngas gasifier is based.

BASIS: 1 HOUR, $T_{\text{base}} = 32^\circ\text{F}$

FLUE GAS

| | LB MOLES | |
|------------------|----------|-------------|
| CO ₂ | 220.9 | 24.09 MMBtu |
| O ₂ | 34.8 | |
| N ₂ | 1439.1 | 4.47 MMBtu |
| H ₂ O | 128.9 | |

MEDIUM-Btu
PRODUCT GAS

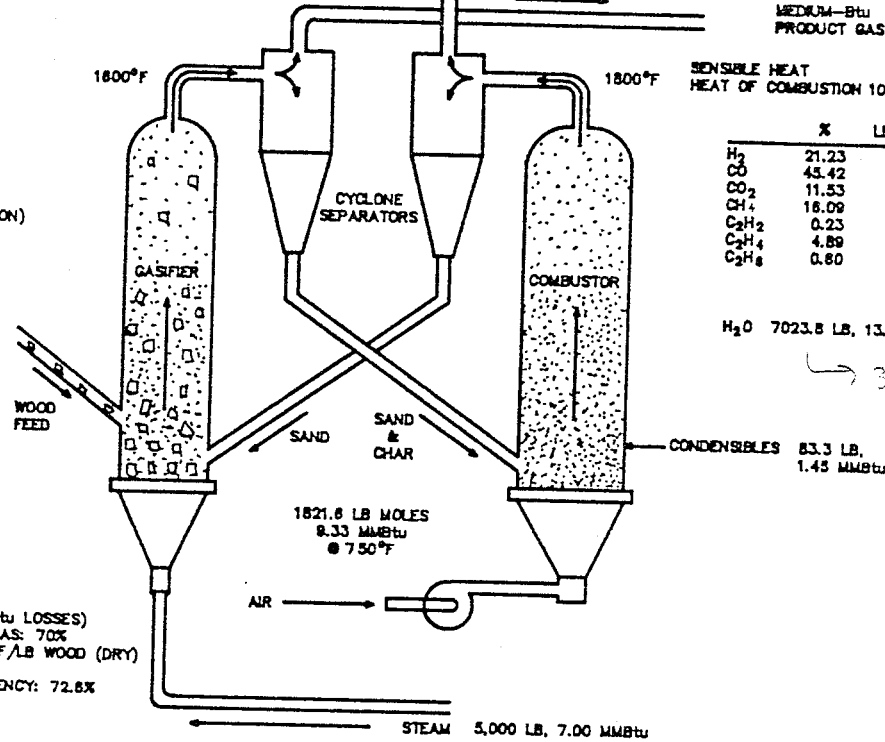
SENSIBLE HEAT 8.97 MMBtu
HEAT OF COMBUSTION 107.79 MMBtu

| | % | LB MOLES |
|-------------------------------|-------|----------|
| H ₂ | 21.23 | 128.1 |
| CO | 43.42 | 274.1 |
| CO ₂ | 11.53 | 68.8 |
| CH ₄ | 18.09 | 97.1 |
| C ₂ H ₂ | 0.23 | 1.4 |
| C ₂ H ₄ | 4.89 | 29.5 |
| C ₂ H ₆ | 0.80 | 3.8 |
| | | 603.4 |

H₂O 7023.8 LB, 13.04 MMBtu

→ 390 lb-mol

Total = 390 + 603.4
= 993.6 lb-mol/hr



HEAT IN: 188.32 MMBtu
HEAT OUT: 188.32 MMBtu
(INC. 8.50 MMBtu LOSSES)
CARBON CONVERSION TO GAS: 70%
GAS PRODUCTION: 13.8 SCF/LB WOOD (DRY)
HHV (DRY): 470 Btu/SCF
COLD GAS THERMAL EFFICIENCY: 72.8%

FIGURE 6. Battelle Columbus Gasifier Test Case at 1600°F.

$7.56 \frac{\text{dry wood}}{\text{dry}} = \left(\frac{1888.7}{2209.1} \right) \leftarrow 18,888.7 \text{ LB (DRY)}$
1851.9 LB MOISTURE
148.33 MMBtu (COMBUSTION)
0.21 MMBtu (SENSIBLE)

TABLE 2. Summary of Conceptual Designs of Integrated Biomass Gasification Plants

| | BCL | Syngas | UM-R |
|---|--|---------------------|---|
| Design Features: | | | |
| Heat Transfer from Product Gas | 1. Steam generation 2. Hot air to dryer | 1. Hot air to dryer | 1. Hot air to dryer |
| Heat Transfer from Combustor Gas | 1. Preheat combustion air 2. Hot air to dryer | 1. Hot air to dryer | 1. Preheat combustion air 2. Steam generation 3. Hot air to dryer |
| Operating Conditions: | | | |
| Temperature of Gasifier, °F | 1600 | 1600 | 1425 |
| Pressure, psig | <15 | <15 | <15 |
| Moisture content of gasifier feed, % | 10 | 10 | 10 |
| Steam rate, lb/lb dry wood* | 0.3 | -- | 0.638 |
| Oxygen, lb/lb dry wood* | -- | 0.481 | -- |
| Performance: | | | |
| HHV of product gas dry Btu/SCF | 470 | 317 | 421 |
| Product gas (dry) composition, % volume | | | |
| C ₂ + | 5.72 | 2.51 | 5.52 |
| CH ₄ | 16.09 | 5.89 | 10.55 |
| CO | 45.42 | 45.86 | 34.31 |
| CO ₂ | 11.53 | 23.98 | 16.76 |
| H ₂ | 21.23 | 21.75 | 31.17 |
| N ₂ | -- | -- | 1.68 |
| Char production**, lb/lb dry*wood* | 0.17 | 0.032 | 0.052 |
| Tar production**, lb/lb dry wood* | 0.005 | 0.017 | 0.056 |
| Carbon conversion to product gas, % | 70.0 | 90.9 | 70.0 |
| Cold gas thermal efficiency, (HHV product gas/HHV woodfeed*), % | 72.6 | 64.3 | 72.2 |
| Product gas (dry) yield SCF/lb dry wood* | 13.8 | 18.7 | 14.3 |

* Based on total wood feed to plant.

**Char and tar assumed completely combusted in integrated plant.

BASIS: 1 HOUR, T_{base} = 32°F

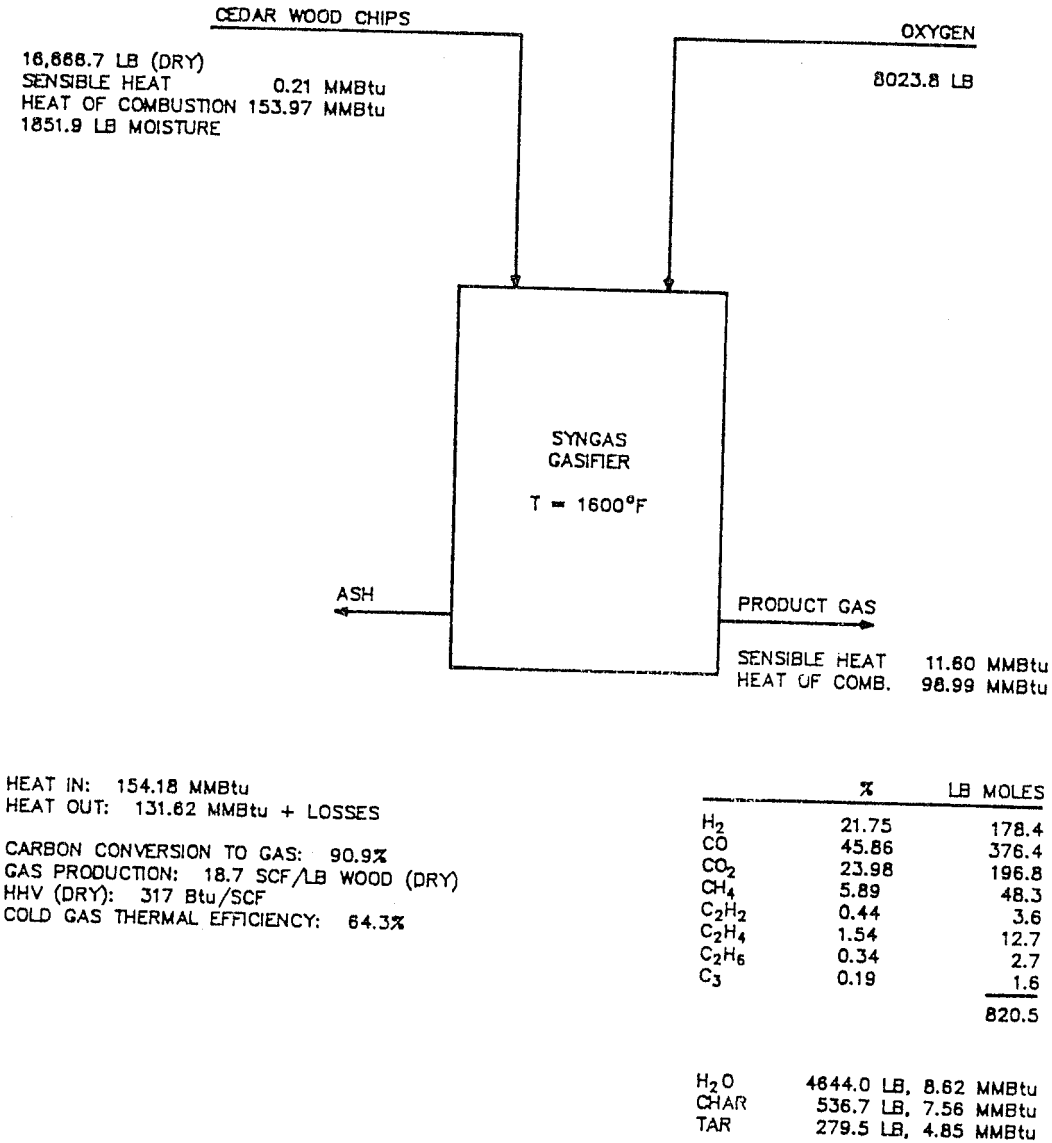


FIGURE 7. Syngas Gasifier Test Case at 1600°F.

The energy balance, which is a reflection of the energy balance for the experimental data, showed significant heat losses amounting to about 15 percent of the heating value of the wood feedstock. If the heat losses in the experimental unit had been better controlled (better insulation, electrical heating to compensate for losses, etc.), the process results would have been different, but they cannot be predicted. Less oxygen probably would have been required. The cold gas thermal efficiency for this test case for the Syngas gasifier is rather low at 64 percent and reflects the fact that heat energy is lost from the system instead of being converted to energy in the product gas.

The results of the calculations done with the assumption that the split of the carbon among the three output products was correct were consistent with the concept that more char and tar are produced at the expense of product gas. The cold gas thermal efficiency was then 61 percent, and somewhat less oxygen was calculated to be required [0.456 lb O₂/lb wood (dry)]. The overall energy balance was little changed, however.

University of Missouri-Rolla Indirect-Fired Fluid Bed. The University of Missouri-Rolla system is designed to use an auxiliary supply of additional feedstock to supply the heat required for gasification. To get the most gas production from the gasifier, it should be operated at the highest practical temperature to give the highest carbon conversion to gas. The system has been operated at 1466°F, but the developers caution against operating it at too high a temperature because the bed may sinter. Consequently, 1425°F was chosen as the bed operating temperature. According to the correlation line shown in Figure 5 for the carbon conversion to gas for this system, the carbon conversion is 80 percent at this temperature. Since steam-to-wood ratio does not influence process performance very much, a minimum steam ratio for this system of 0.733 lb steam/lb wood (dry) was selected. The product gas composition was obtained by averaging the values for the various components found for runs above 1389°F, there being no clear correlation of gas composition for interpolating the values.

The amount of heat required to be supplied via indirect heat transfer through the tubes was found from a heat balance around the medium-Btu gasifier. Then the amount of additional wood feedstock required to supply this heat was found, with the assumption that the tar and the char from the medium-Btu gasifier would be recycled back to the low-Btu gasifier/combustor to supply part of the heat. To provide an adequate temperature difference for heat transfer and waste heat recovery, the flue gas was assumed to exit the system at 1875°F. The low-Btu gasifier/combustor was assumed to be supplied with 25 percent excess air for complete combustion. The combustion air was assumed to be preheated to 750°F. The conditions calculated for the gasifier for this test case for the University of Missouri-Rolla system are shown in Figure 8 and Table 2. The entire system was scaled to require a total biomass feedstock of 200 TPD for gasification and auxiliary combustion for comparison with the other systems.

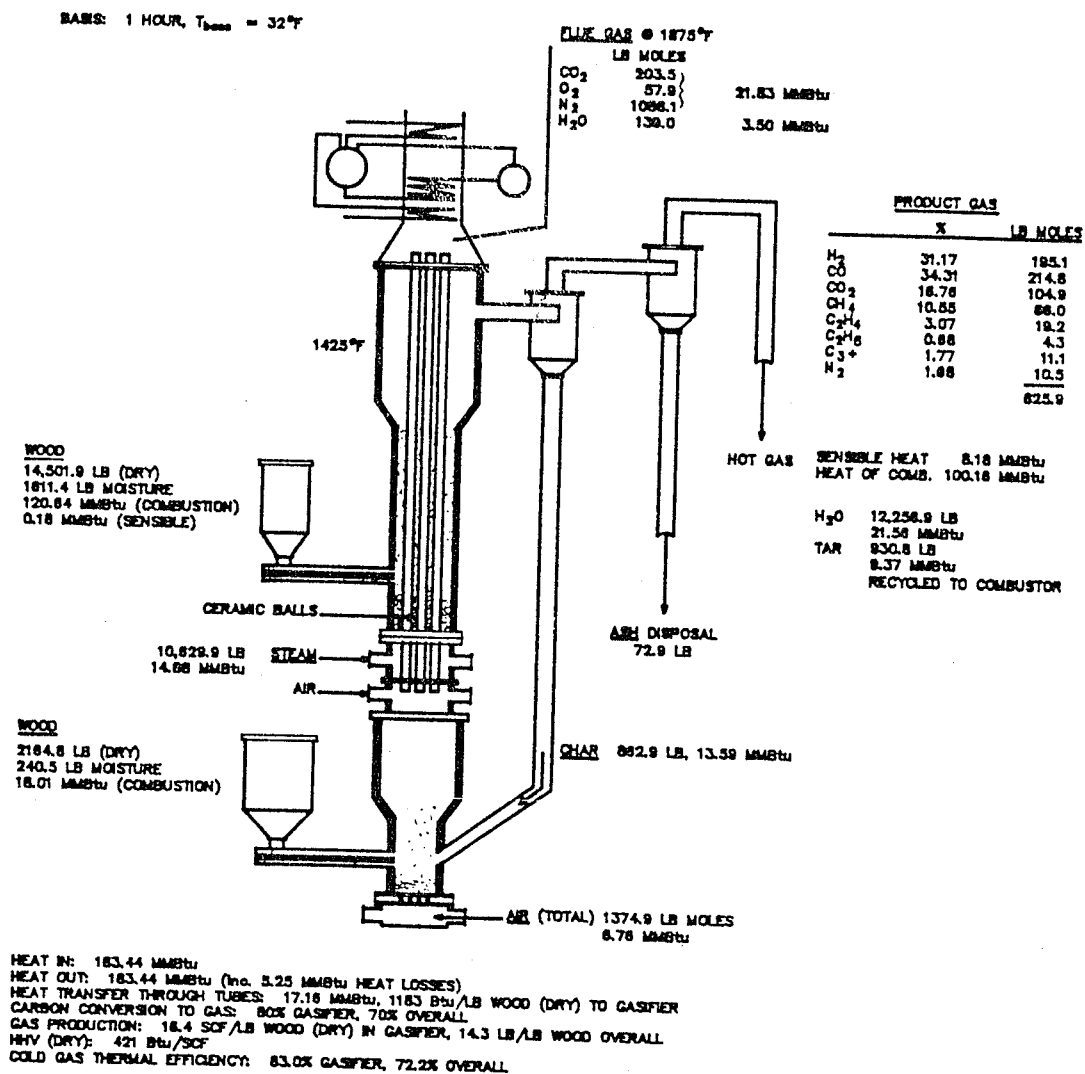


FIGURE 8. University of Missouri-Rolla Gasifier Test Case at 1425°F.

In addition to the test case calculated at the high temperature of 1425°F, a low-temperature case was calculated at 1225°F. The idea was that at a lower temperature, albeit at a somewhat lower carbon conversion to gas, the heat transfer between the medium-Btu gasifier and the low-Btu gasifier/combustor would be more efficient, perhaps leading to a better cold gas thermal efficiency for the entire system. At an average bed temperature of 1225°F, the carbon conversion to gas was 74 percent.

However, the calculations revealed that under these conditions, more char and tar would be produced than would be needed to supply the heat transferred into the medium-Btu gasifier. The efficiency of the system would then suffer because some char and tar would be thrown away rather than used beneficially. The cold gas thermal efficiency was found to be 70 percent for this case.

It should be possible to visualize a case in which sufficient char and tar would be produced in the medium-Btu gasifier to fuel the low-Btu gasifier/combustor. The system could then be operated without the use of extra wood feedstock. The energetics of the system in this case would be similar to those of the Battelle Columbus system operating in a balanced mode between gasification and combustion.

Integrated 200-TPD Biomass Gasification Plants

In this section conceptual designs of integrated 200-TPD biomass gasification plants are discussed. These integrated plants were designed around the test cases which were calculated for the three gasifiers evaluated in this study and discussed in a preceding section.

The input to each integrated plant was assumed to be woodchip feedstock and its output medium-Btu fuel gas. The purpose of developing designs for integrated plants was to compare gasifier designs on the basis of overall system efficiencies which would consider the possible need for auxiliary fuel, either to dry the incoming green woodchips or to raise the steam that may be needed for the gasification process. Table 2 summarizes the main design features of the integrated plants as well as the overall performance characteristics.

Battelle Columbus Laboratory Plant. Based on the test case for the BCL gasifier described above, a conceptual design for an integrated 200-TPD biomass gasification plant was developed. This design is shown in Figure 9. This integrated plant was designed to dry the incoming green woodchips and to generate the necessary steam with waste heat.

The energy flows in Figure 9 were calculated assuming a base temperature of 32°F and liquid water having an enthalpy of zero. Materials such as air, green woodchips, and water at ambient conditions were assumed to be available at 60°F.

Two hot streams are available from which waste heat can be recovered or used--the hot product gas from the gasifier and the hot flue gas from the combustor. The hot product gas must be kept separate from other streams and not mixed, so that its heat can be recovered only by means of indirect heat exchange. As shown in Figure 9, the hot

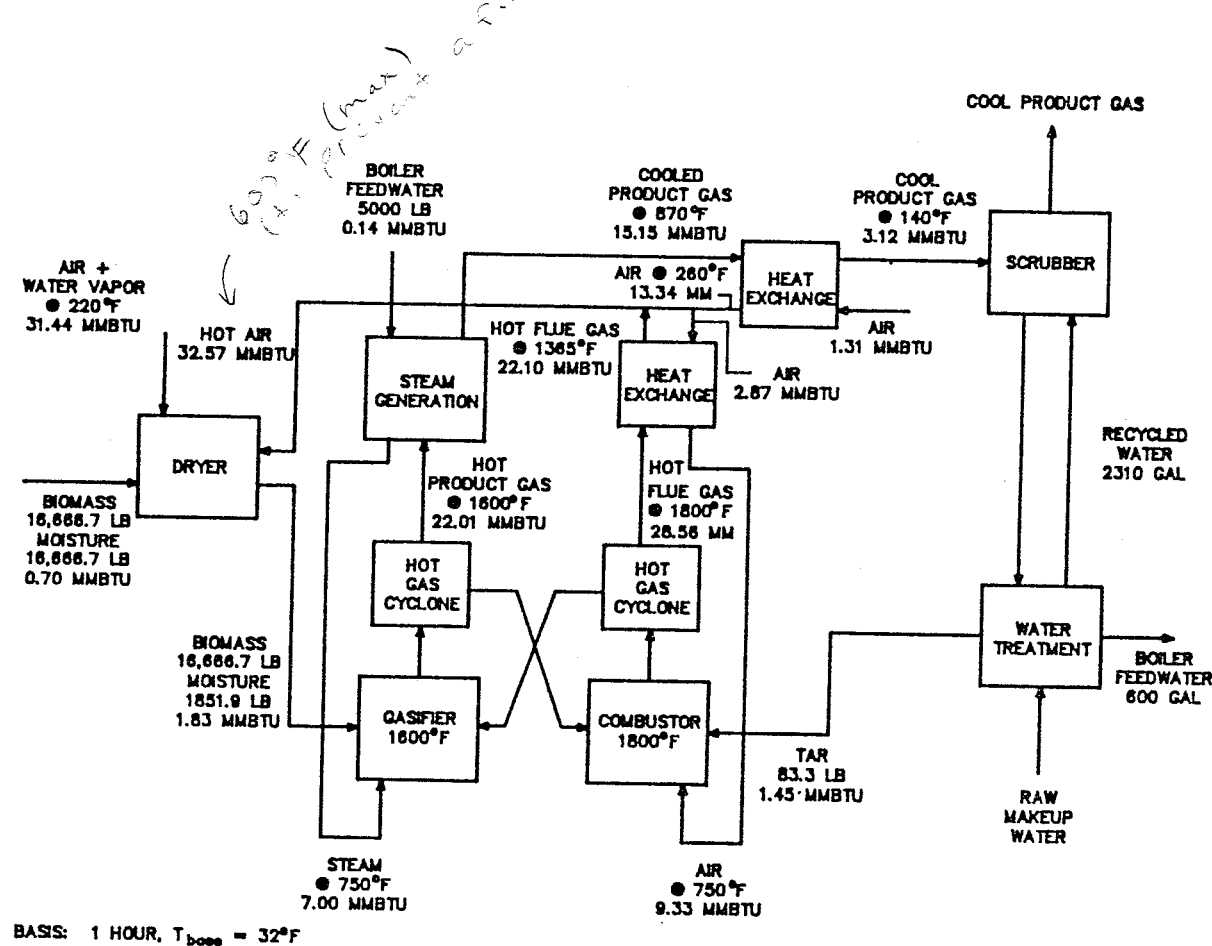


FIGURE 9. Material and Thermal Energy Flows for 200-TPD Integrated Battelle Biomass Gasification Plant.

product gas is used for generating the required process steam used in the gasifier and then for heating air. A portion of this preheated air is heated further up to 750°F by means of heat exchange with the hot flue gas from the combustor. This hot air is then used as the combustion air for combusting the char and the tar.

The hot flue gas is first used to heat up the combustion air from 260°F to 750°F. The flue gas is then mixed directly with the bulk of the preheated air to provide a stream of essentially hot air at a temperature of no more than 600°F. This stream of hot air is then suitable for drying the green woodchips directly in the rotary dryer. The dryer is assumed to heat the woodchips up to a maximum temperature of 220°F. The temperature of the stream of hot air used for chip drying is limited to a maximum of 600°F; a higher temperature could set the woodchips on fire.

The integrated plant design in Figure 9 appears to be balanced with respect to thermal energy requirements. However, provision for estimates of heat losses from equipment and a detailed analysis of the hot product gas/air heat exchanger could force an adjustment of operating conditions to rebalance the plant.

Syngas Plant. Based on the test case for the Syngas gasifier, a conceptual design for an integrated 200-TPD biomass gasification plant was developed. This design is shown in Figure 10. This integrated plant was designed to dry the incoming green woodchips with waste heat. No steam generation is required because the gasifier is designed to operate without steam. Although no steam generation is required, both potential sources of waste heat--the hot product gas and the char and tar--are needed to provide the required amount of hot air for woodchip drying. In Figure 10 the hot product gas is shown heating up the air for the dryer to a temperature of 350°F.

The char recovered from the hot product gas via the hot gas cyclones and the tar scrubbed out of the product gas are sent to the combustor. In the combustor these materials are burned to provide a hot flue gas, which is mixed directly with the preheated air stream. The combined stream has a temperature of 600°F, which is suitable for the woodchip dryer.

Based on test data, the gasifier appears to lose a great deal of thermal energy. If the gasifier were designed to be more conservative of heat, just where the heat which is saved would show up cannot be easily predicted. A greater quantity of gas could be produced, or since less oxygen would probably be used, the gas could have a different composition with a greater heat of combustion. The point to be made here is that better test data are needed to more precisely determine the performance of the Syngas type of gasification system.

University of Missouri-Rolla Plant. Based on the test case for the UM-R gasifier, a conceptual design for an integrated 200-TPD biomass gasification plant was developed. This design is shown in Figure 11. In this integrated plant waste heat is used to dry the incoming green woodchips to the 10 percent moisture level and to generate the required process steam.

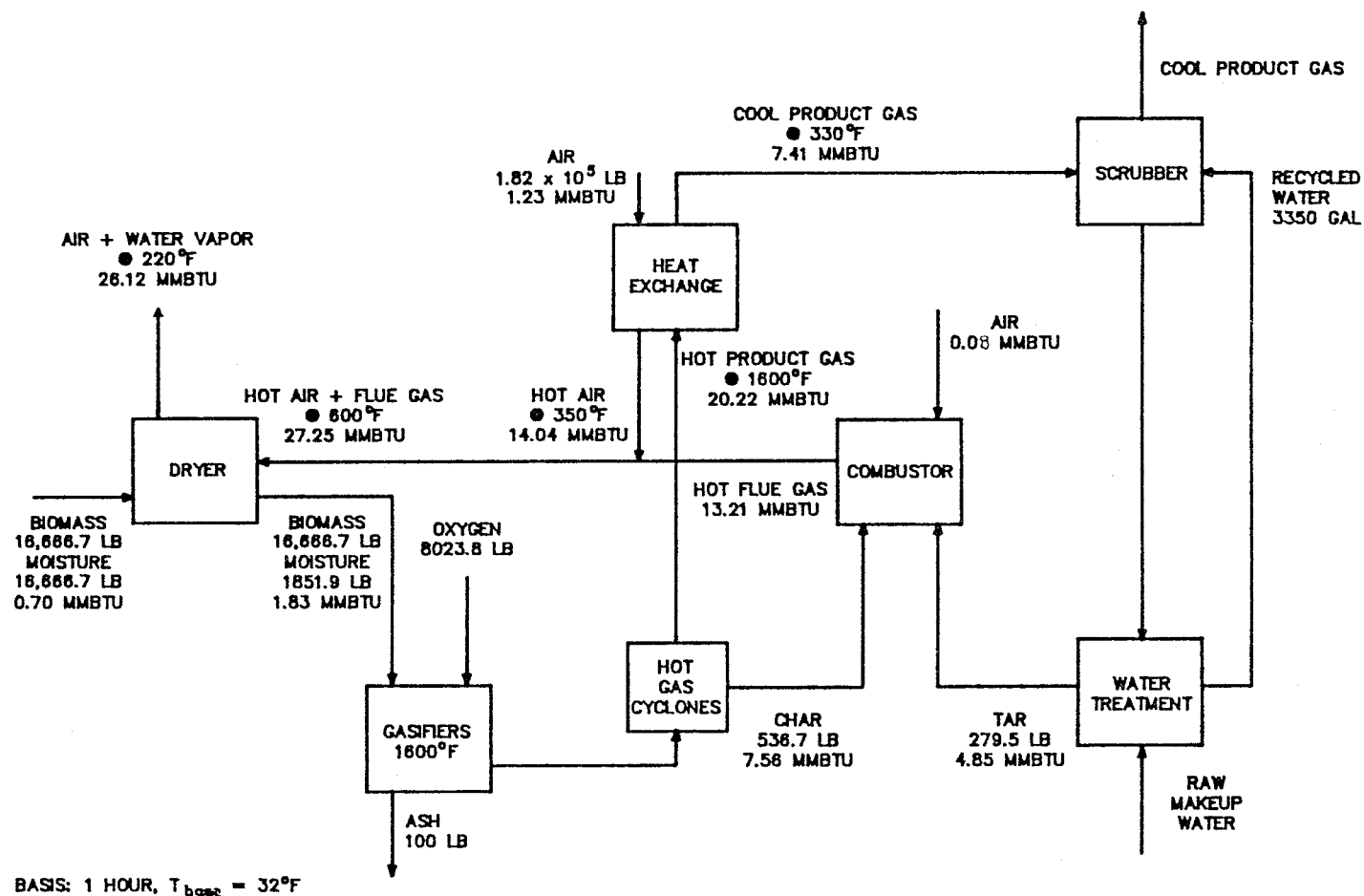


FIGURE 10. Material and Thermal Energy Flows for 200-TPD Integrated Syngas Biomass Gasification Plant.

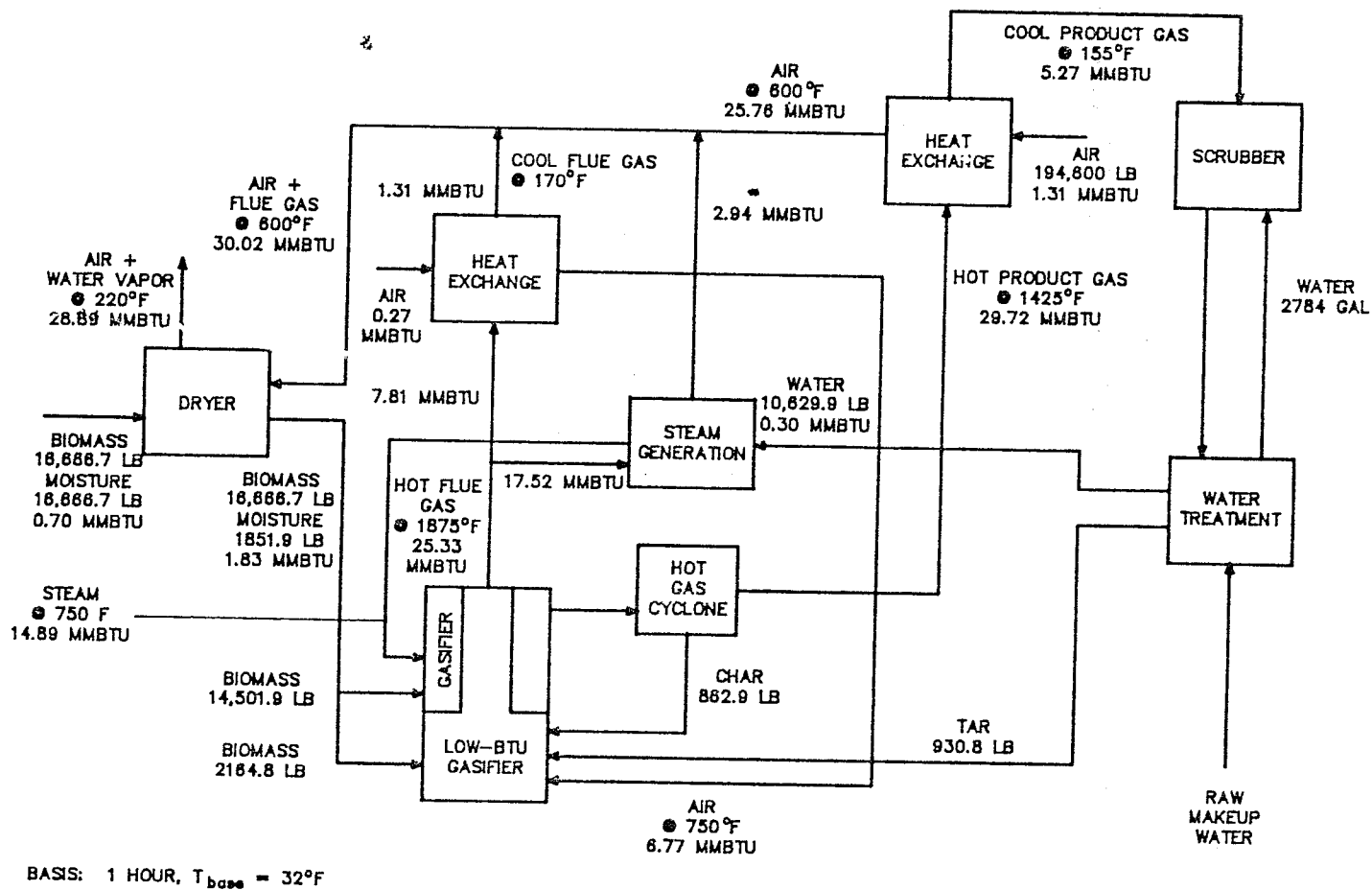


FIGURE 11. Material and Thermal Energy Flows for 200-TPD Integrated UM-R Biomass Gasification Plant.

The UM-R plant has the same two hot streams available for recovery of waste heat as the other types of biomass gasification plants: the hot product gas stream, and hot flue gas resulting from combustion. However, the UM-R gasifier is designed with a built-in combustor, and the unit has been operated and tested under conditions requiring the combustion of additional biomass feedstock besides the char and the tar resulting from the gasification process. The basic gasifier design also includes steam generation from the hot combustion flue gas, which first provides indirect heat to drive the gasification process and to produce the medium-Btu product gas. The hot product gas is used to heat the air going to the dryer, and a maximum amount of this heat must be recovered. The cooled flue gas is mixed directly with the hot air stream to condition this stream to a maximum temperature of 600°F before it enters the woodchip dryer.

Summaries of Plant Material and Energy Inputs and Outputs

The flows of materials and energy into and out of the 200-TPD plants were calculated and summarized for the three different gasification processes. The total electrical power requirements included the electricity usage for feedstock handling and drying, the electricity usage for gasification, and the power required for the scrubber. For the Syngas plant, which requires oxygen, an amount of electricity for producing the oxygen used in the gasifier was included as an energy input, and this electricity was expressed in terms of its primary energy equivalence for the purpose of being included in the overall energy efficiency based on total primary energy input.

Table 3 summarizes the energy efficiencies for the three different plant designs for both 200-TPD and 1000-TPD plants. The cold gas thermal efficiency is unaffected by plant size. The next section below discusses the overall energy efficiencies for 1000-TPD plants.

Integrated 1000-TPD Biomass Gasification Plants

The conceptual designs for 1000-TPD biomass gasification plants based upon the different gasifiers were identical to the designs shown in Figures 9 through 11 for 200-TPD plants. The only difference is, of course, that material and energy flows were scaled upward by a factor of 5. The main difference in energy requirements for a 200-TPD plant and a 1000-TPD plant--at this level of analysis--is in the electricity usage. For the larger plant there is a small relative saving in electricity in the feedstock handling and storage system. The overall energy efficiencies for 1000-TPD plants are also shown in Table 3.

TABLE 3. Plant Energy Efficiencies.

| Gasification Plant | Cold Gas Thermal Efficiency, % | Overall Energy Efficiency, % | |
|------------------------------|--------------------------------|------------------------------|----------------|
| | | 200-TPD Plant | 1000-TPD Plant |
| Battelle Columbus | 72.6 | 68.9 | 69.3 |
| Syngas | 64.3 | 56.8 | 57.1 |
| University of Missouri-Rolla | 72.2 | 68.2 | 68.6 |

ECONOMIC ANALYSIS OF CONCEPTUAL DESIGNS OF INTEGRATED PLANTS

This section presents the economics of the gasification of woody biomass to generate a medium-Btu gas based on the detailed process analyses and conceptual process designs described above. Specifically, the economic results include the following:

- Detailed breakdown of integrated gasification plant capital investment requirements
- Detailed breakdown of annual operating and maintenance costs
- Cost summary and product gas cost per million Btu

The objective of this economic analysis is to compare the basic individual merits of the three gasification processes. To avoid introducing a feedstock variable--the type and form of feedstock--into the analysis, the same type of feedstock, whole woodchips, has been assumed for each case. The assumption of woodchips as feedstock makes the feedstock handling and storage systems the same for all case. Assuming the use of hog fuel for one system and woodchips for another would give the hog-fueled system an economic advantage in terms of the cost of the gas produced because hog fuel is a cheaper feedstock.

Capital Investment Requirements

The capital investment requirement consists of all capital necessary to complete the entire production plant project. This capital requirement includes installed equipment costs, engineering and fee, contingency, working capital, interest during construction, and start-up costs. Among the total installed equipment costs, the major cost items are costs associated with five process areas: wood handling and storage, gasifier and combustor, steam generation, heat recovery, and wastewater treatment. The installed capital costs of major process equipment were estimated from published cost data. The capital cost estimates are based on mid-1986 pricing; a cost index was used to escalate the equipment costs and pricing derived from earlier cost data.

As a basis for estimating the capital costs of gasifiers, the data in a recent reference on costs of air-blown biomass gasifiers (7) were correlated and analyzed. The cost data for downdraft gasifiers and for fluidized-bed gasifiers were used to calculate a least-squares line (on a log-log plot) for each gasifier type. Because these cost data were for systems with air-blown gasifiers which produce low-Btu gas, these data were adjusted before they were applied to oxygen-blown or medium-Btu gasifiers, which operate at different (higher) throughput rates than do air-blown gasifiers. The necessary adjustment of the cost of the gasifier by itself was done in terms of the feed rate or throughput.

The data on throughput rate for gasifiers (8) were used to estimate the largest practical sizes for downdraft and fluidized-bed gasifiers, after appropriate adjustments for the difference in throughput rates between air-blown and oxygen-blown gasifiers. With respect to the scale-up of downdraft gasifiers, it was estimated that the largest downdraft gasifier operating with oxygen which can be conceived with present technology would use between 4 and 8 oven-dry tons/hr of biomass feed (96 and 192 oven-dry tons/day). For the purposes of the economic analysis, it was assumed that a 200-TPD plant would require two 100-TPD downdraft gasifiers and a 1000-TPD plant would require eight, each with a capacity of 125 TPD.

down draft

one → The University of Missouri-Rolla gasifier is basically a fluidized-bed gasifier. The largest UM-R gasifier thought to be practical is about 12 feet in diameter, which would be suitable for the 200-TPD plant (the actual feed rate through the medium-Btu gasifier is less than this, at 174 TPD). The 1000-TPD UM-R plant would require six gasifiers.

The overall capital requirements for the four gasification plants are summarized in Table 4. Inspection of the results shows that:

- Among the installed equipment costs, the largest cost items are associated with the wood handling and storage, gasifier, and wastewater treatment areas.
- The total capital requirements for an integrated wood gasification plant is estimated to range from \$6.08 to \$7.13 MM for a 200-TPD plant, depending on the process design and operating characteristics. The lowest capital cost corresponds to the Syngas gasification system, while the highest capital requirement occurs for the UM-R system.
- For 1000-TPD plants the total capital requirement ranges from \$22.9 MM for the BCL system to \$31.8 MM for the UM-R system.

1986 dollars

TABLE 4. Total Capital Requirements for Integrated Biomass Gasification Plants.

| Gasification System Feed Capacity, TPD | Capital Requirements, \$10 ³ * | | | | | |
|---|---|---------------|-------------|-------------|---------------|---------------|
| | BCL | | Syngas | | UM-R | |
| | 200 | 1000 | 200 | 1000 | 200 | 1000 |
| Wood Handling and Storage (number of dryers) | 1703 (1) | 7653 (2) | 1703 (1) | 7653 (2) | 1703 (1) | 7653 (2) |
| Combustion for Dryer | -- | -- | 179 | 526 | -- | -- |
| Gasifier** (number of gasifier systems) | 1342** (1) | 4560** (2) | 1028 (2) | 4834 (8) | 1429** (1) | 7583** (6) |
| Combustor for Steam Generator | -- | -- | -- | -- | -- | -- |
| Steam Generator | 604 | 1500 | -- | -- | 720 | 4128 |
| Air/Flue Gas Heat Exchanger | 52 | 69 | -- | -- | 75 | 144 |
| Air/Product Gas Heat Exchanger | 107 | 202 | 87 | 168 | 142 | 272 |
| Wastewater Treatment**** | 754 | 1924 | 810 | 2200 | 868 | 2443 |
| Total Installed Equipment Cost | 4562 | 15908 | 3807 | 15381 | 4937 | 22233 |
| Engineering and Fee | 456 | 1591 | 381 | 1538 | 494 | 2222 |
| Project Contingency | 684 | 2386 | 571 | 2307 | 741 | 3333 |
| Total Plant Investment (TPI) | 5702 | 19885 | 4759 | 19226 | 6172 | 27778 |
| Interest During Construction | 456 | 1591 | 381 | 1538 | 494 | 2222 |
| Start-Up Cost | 268 | 783 | 800 | 3362 | 277 | 961 |
| Working Capital | 171 | 597 | 142 | 577 | 185 | 833 |
| Total Capital Requirement | 6597 | 22,856 | 6082 | 24,703 | 7128 | 31,794 |

* 2nd Quarter, 1986 dollars.

** Including combustor.

→ *** Including feeder system, hot gas cyclone, and scrubber.

****Including demineralizer.

Operating and Maintenance Costs

The biomass gasification plants are assumed to operate on a continuous basis with an annual plant capacity factor of 90 percent. The operating requirements include raw materials, utilities, materials and chemicals, and operating labor. The raw material and utility requirements for the process are primarily functions of process efficiency and design. The annual operating and maintenance costs for each of the four gasification processes were calculated, based on estimated labor requirements and assumed costs for utilities, and the detailed results are presented in Table 5. The significant findings of these results are summarized below.

- Raw material contributes approximately 5 percent of the total O&M costs for non-oxygen systems (BCL & UM-R). For oxygen-blown systems the oxygen costs alone can account for nearly 60 percent of the total O&M costs.
- Purchased electricity accounts for 15-20 percent of the total O&M costs.
- Labor-related costs contribute to 20-30 percent of the total O&M costs.

Medium-Btu Gas Production Cost

Based on the estimated capital investment and annual O&M costs, medium-Btu gas production costs were calculated using a discount cash flow (DCF) calculation. There are two potential methods of financing a plant of this type: utility financing and private investor financing. Gas production costs were calculated using both procedures. The major assumptions used in the economic analyses are:

- All costs in mid-1986 dollars
- Tax life - 20 years
- Plant life - 20 years
- 8 percent annual interest rate on debt
- 15 percent after-tax return on equity
- 48 percent federal income tax rate
- 90 percent plant factor at startup year and thereafter
- Debt/equity ratio: 75/25 for utility, 0/100 for private
- Straightline depreciation

TABLE 5. Comparison of Operating and Maintenance Costs for Biomass Gasification Plants

Costs*, \$10³ (1986 dollars)

| Gasification System | BCL | | Syngas | | UM-R | |
|--|------|------|--------|-------|------|------|
| | 200 | 1000 | 200 | 1000 | 200 | 1000 |
| Feed Capacity, TPD | | | | | | |
| Raw Materials | | | | | | |
| Oxygen | --- | --- | 2530 | 12652 | --- | --- |
| Lime | 22 | 108 | 27 | 135 | 29 | 146 |
| Solid Waste Disposal | 3 | 16 | 3 | 16 | 3 | 16 |
| Chemicals and Sand | 24 | 119 | --- | --- | 26 | 130 |
| Utilities | | | | | | |
| Electricity | 320 | 1600 | 325 | 1631 | 322 | 1612 |
| Labor | | | | | | |
| Process Operating | 433 | 649 | 540 | 865 | 433 | 865 |
| Maintenance | 109 | 382 | 91 | 369 | 122 | 550 |
| Supervision | 87 | 130 | 149 | 173 | 87 | 173 |
| Admin. and Overhead | | | | | | |
| Operating | 130 | 195 | 162 | 260 | 130 | 260 |
| Maintenance | 73 | 255 | 61 | 246 | 81 | 367 |
| Taxes and Insurance | 137 | 461 | 114 | 461 | 152 | 687 |
| Total Annual Operating & Maintenance Costs | 1338 | 3915 | 4002 | 16808 | 1385 | 4806 |

*Excluding wood feedstock cost

Table 6 summarizes the gas production economics resulting from the DCF calculations for 200-TPD plants financed as regulated utility ventures for all four gasification plant types. These gas production costs are presented in terms of annual O&M costs and capital charges, and at three different feedstock costs, \$25.50/ton (\$1.50/MMBtu), \$34/ton (\$2/MMBtu), \$42.50/ton (\$2.50/MMBtu). Similarly, Table 7 summarizes the gas production costs with private financing. An examination of these gas production costs reveals the following findings:

- Without considering wood feedstock costs, the annual production costs for a 200-TPD biomass gasification plant range from \$2.29 MM to \$4.88 MM for utility financing. These figures correspond to a gas production cost range of from \$2.81/MMBtu to \$6.77/MMBtu.
- Excluding feedstock costs, the annual production costs for a 200-TPD biomass gasification plant range from \$3.06 MM to \$5.58 MM for private financing. These costs correspond to a gas production cost of between \$3.75/MMBtu and \$7.74/MMBtu.
- With feedstock cost ranging from \$1.50/MMBtu to \$2.50/MMBtu and for utility financing, the lowest medium-Btu gas production cost is for the BCL system (\$4.88-6.25/MMBtu), followed by the UM-R system (\$5.07-6.45/MMBtu). The Syngas oxygen-blown gasification system has the highest production cost (\$9.10-10.66/MMBtu).

Tables 6 and 7 include the estimated gas production costs of 1000-TPD biomass gasification plants for regulated utility financing and private financing ventures, respectively. As can be seen, the gas production costs, excluding feedstock cost, range from \$1.77/MMBtu to \$5.66/MMBtu for these large-size plants with utility financing. With feedstock cost included, gas production costs range from \$3.84/MMBtu to \$9.55/MMBtu. These costs are about \$0.70-1.10/MMBtu lower than the gas production costs for a 200-TPD plant. For private financing, the gas production costs are about \$0.78-1.34/MMBtu lower for a 1000-TPD plant versus a 200-TPD plant. This decrease in cost results from a lower proportion of capital charges and non-feedstock O&M costs, as compared with the production costs for a smaller plant. In practice, these lower costs for the larger conversion plant may be offset by a higher cost for the large quantity of biomass feedstock.

TABLE 6. Summary of Medium-Btu Gas Production Economics, Utility Financing
%

| Gasification System | BCL | | Syngas | | UM-R | |
|--|-------|------|--------|------|-------|------|
| | 200 | 1000 | 200 | 1000 | 200 | 1000 |
| Feed Capacity, TPD | | | | | | |
| Feedstock, 10 ³ dry tons per year | 66 | 330 | 66 | 330 | 66 | 330 |
| M-Btu Gas, 10 ¹² Btu per year* | 0.815 | 4.08 | 0.721 | 3.60 | 0.810 | 4.05 |
| Annual O&M Costs, \$MM | 1.34 | 3.92 | 4.00 | 16.8 | 1.39 | 4.81 |
| Capital Charges including 15% return on equity, \$MM | 0.954 | 3.30 | 0.879 | 3.57 | 1.03 | 4.59 |
| Total Annual Production Costs, excluding feedstock | | | | | | |
| \$MM | 2.29 | 7.22 | 4.88 | 20.4 | 2.42 | 9.40 |
| \$MMBtu | 2.81 | 1.77 | 6.77 | 5.66 | 2.99 | 2.32 |
| Total Annual Production Cost, \$/MMBtu with Feedstock Cost at | | | | | | |
| \$1.50/MMBtu or \$25.50/ton | 4.88 | 3.84 | 9.10 | 7.99 | 5.07 | 4.40 |
| \$2.00/MMBtu or \$34.00/ton | 5.56 | 4.52 | 9.88 | 8.77 | 5.76 | 5.09 |
| \$2.50/MMBtu or \$42.50/ton | 6.25 | 5.21 | 10.66 | 9.55 | 6.45 | 5.78 |

*For this comparison the gas production has been taken as the heat of combustion of the biomass feedstock (17 MMBtu/dry ton) multiplied by the cold gas thermal efficiency.

TABLE 7. Summary of Medium-Btu Gas Production Economics, Private Financing

| Gasification System | BCL | | Syngas | | UM-R | |
|--|-------|------|--------|-------|-------|------|
| | 200 | 1000 | 200 | 1000 | 200 | 1000 |
| Feed Capacity, TPD | | | | | | |
| Feedstock, 10 ³ dry tons per year | 66 | 330 | 66 | 330 | 66 | 330 |
| M-Btu Gas, 10 ¹² Btu per year* | 0.815 | 4.08 | 0.721 | 3.60 | 0.810 | 4.05 |
| Annual O&M Costs, \$MM | 1.34 | 3.92 | 4.00 | 16.8 | 1.39 | 4.81 |
| Capital Charges including 15% return on equity, \$MM | 1.72 | 5.96 | 1.58 | 6.45 | 1.86 | 8.29 |
| Total Annual Production Costs, Excluding Feedstock | | | | | | |
| \$MM | 3.06 | 9.88 | 5.58 | 23.3 | 3.25 | 13.1 |
| \$MMBtu | 3.75 | 2.42 | 7.74 | 6.46 | 4.01 | 3.23 |
| Total Annual Production Cost, \$/MMBtu with Feedstock Cost at | | | | | | |
| \$1.50/MMBtu or \$25.50/ton | 5.82 | 4.48 | 10.07 | 8.79 | 6.09 | 5.31 |
| \$2.00/MMBtu or \$34.00/ton | 6.50 | 5.17 | 10.85 | 9.57 | 6.78 | 6.00 |
| \$2.50/MMBtu or \$42.50/ton | 7.19 | 5.86 | 11.63 | 10.35 | 7.47 | 6.69 |

*For this comparison the gas production has been taken as the heat of combustion of the biomass feedstock (17 MMBtu/dry ton) multiplied by the cold gas thermal efficiency.

CONCLUSIONS

As the result of the technoeconomic evaluation in this study of three advanced biomass gasification processes, a number of conclusions and recommendations were developed in several areas. These conclusions and recommendations are listed and discussed in this section.

- For production of low-pressure fuel gas, the BCL gasification system appears to offer some significant advantages over the other gasifier types: less stringent specifications in size, type, and moisture level of the feed; higher heating value of the product gas; higher throughput rates; fewer condensibles (tar) produced; easier gas cleanup.
- The BCL and the UM-R gasifiers are designed on the basis of the same advantages: separation of the gasification reactions from the combustion which provides the necessary heat. However, the BCL gasifier is designed to utilize direct heat transfer, which is more efficient than the indirect heat transfer in the UM-R system with temperature gradients across heat-transfer interfaces. The UM-R system is more difficult to operate to avoid getting hot spots to plug up the bed, etc. The UM-R system also requires more stringent specifications on the feedstock.
- The capital costs of the three different integrated plants are not greatly different, but this result should perhaps not be surprising. After all, the thermal efficiencies of the plants do not greatly differ, leading to similar heat-exchange requirements and similar costs in this area. Feedstock handling and storage costs are the same, as are costs for gasifier feed systems. With respect to the gasifier itself, the Battelle gasifier has by far the highest throughput rate and the least complex reactor, and so should be the cheapest. The Syngas and UM-R reactors have complex internals and by far the lowest throughput rates, and so should be the most expensive.
- For the Syngas oxygen-blown system, oxygen costs can alone account for nearly 60 percent of the total O&M costs, and for 17 percent or more of the total product gas cost.
- For non-oxygen systems (BCL and UM-R), feedstock cost can account for 35 to 55 percent of the product gas cost. O&M costs and capital charges each roughly account for 50 percent of the remainder, depending on method of financing.

- Based on the assumptions and the data used in this analysis, the cost of low-pressure fuel gas is cheapest from a BCL system, then from UM-R and Syngas systems, in that order.

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